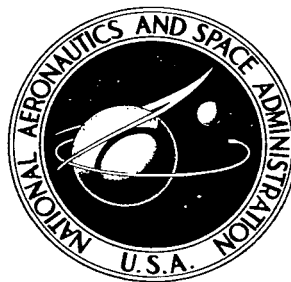


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**FLAMMABILITY IN
ZERO-GRAVITY ENVIRONMENT**

by J. H. Kimzey, W. R. Downs, C. H. Eldred, and C. W. Norris
Manned Spacecraft Center
Houston, Texas



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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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ABSTRACT

Paraffin and other combustibles were burned in a zero-gravity environment. Zero-gravity intervals of 12 seconds, maximum duration, were obtained in the cabin of an aircraft flying Keplerian parabolas. Experiments were photographed with infrared sensitive film at 100 frames per second and 16-mm color film (ER-B) at 200 frames per second. Test results indicate that ignition is essentially unchanged compared to a one-gravity environment but that combustion is suppressed, in some instances, to the extent that the fire appeared to be extinguished. In all cases, the flame was brightest during periods of acceleration, such as at impact of the test chamber with the aircraft and when returning to level flight. Flame conditions at zero gravity were typical of those expected of a pure diffusion flame in which steady-state conditions were not achieved.

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SUMMARY

Paraffin and other combustibles were burned in a zero-gravity environment. Zero-gravity intervals of 12 seconds, maximum duration, were obtained in the cabin of an aircraft flying Keplerian parabolas. Experiments were photographed with infrared sensitive film at 100 frames per second and 16-mm color film (ER-B) at 200 frames per second. Test results indicate that ignition is essentially unchanged compared to a one-gravity environment but that combustion is suppressed, in some instances, to the extent that the fire appeared to be extinguished. In all cases, the flame was brightest during periods of acceleration, such as at impact of the test chamber with the aircraft and when returning to level flight. Flame conditions at zero gravity were typical of those expected of a pure diffusion flame in which steady-state conditions were not achieved.

INTRODUCTION

The pure oxygen atmosphere selected for present manned spacecraft programs has many weight-saving advantages. Use of 100 percent oxygen, however, has created concern about fire safety. Experience from Project Mercury has quieted some fears in this area; yet, it is recognized that many materials are flammable in the oxygen-rich environment of manned spacecraft. The continued use of a pure oxygen atmosphere for the flights of the longer duration Gemini and Apollo Programs, the lower leakage rates, and the increased amount of equipment, have prompted a study of fire extinguishment. The seriousness of the fire hazard problem, at present, requires further investigation.

BACKGROUND

Toxic and flammable contamination of the oxygen-rich atmosphere of manned spacecraft is discussed in reference 1. The factors necessary for ignition, including effects of gravitational force fields, are discussed in detail. Experimental work to investigate combustion during weightlessness was first performed by Hall (ref. 2). Other published experimental work was that of Kamagai and Isoda (ref. 3), where liquid droplets were used as fuel in a falling chamber. Reference 3 notes that for periods of weightlessness as long as 0.32 second, the flame diameter increased. It was hypothesized that in the absence of gravity-induced convection, the products of combustion could blanket the fuel and cause self-extinguishment.

Various means of providing a zero-gravity environment were examined. Free fall from an aircraft was eliminated because of the complexity of equipment needed for a recoverable package which would require equipment for ignition and photography. Another disadvantage of free fall is the gradually increasing drag which can only be overcome by a propulsion device with gradually increasing thrust to maintain an acceleration equal to the gravity of the earth. Use of a drop tower was not considered because of the short time intervals possible with available facilities. The use of aircraft flying a Keplerian parabola at controlled speeds was selected as the most practical test method for initial experiments. A prime advantage of using aircraft is that control personnel could be near the equipment. The duration of weightlessness attainable using aircraft was reported by Wright-Patterson Air Force Base (WPAFB) personnel to be in the range of 9 to 10 seconds with a possibility of 14 to 25 seconds depending on whether the C-131 airplane or KC-135B airplane was used. Flammability testing was conducted on flights during January 1964, utilizing U.S. Air Force support.

ONE-GRAVITY TESTS

A series of tests was performed in a one-gravity environment. Fuels were selected, ignition techniques were developed, and photography was evaluated. Techniques were also developed for preparing the fuel, filling the flammability chambers, and withdrawing samples of the combustion products for chemical analysis.

Equipment Design

Features of the design included means of energizing a Nichrome wire igniter, provisions for holding the fuel, and methods for evacuating gases and refilling with any gas combination at atmospheres ranging from less than 1 psia to approximately 50 psia. A camera bracket for a 16-mm Milliken DBM-5A camera was provided so that motion pictures at various speeds could be made through a pyrex viewing port. Combustion products could be held at reduced pressure for postflight analysis. The metal structure of the chamber was anodized aluminum. The internal volume for the chamber was 0.782 cubic foot. A diagram of the flammability chamber is shown in figure 1.

Fuels

Preliminary tests were made with various materials to develop ignition and photographic requirements and to determine the internal pressures that could result from combustion. Paraffin, a simple hydrocarbon, was selected as one fuel. Previously fired asbestos fiber was added to the paraffin to provide wicking and to reduce excessive dripping. Weight ratios of asbestos to paraffin of 1: 5 to 1: 8 were found to be adequate. Other fuels were selected for their ability to produce soot as in neoprene; for their physical structure, as in foam rubber; and for their capability of producing a tar or resin while burning as occurs in the combustion of nylon. Gases and liquids were eliminated as fuels for flight tests because of danger from an explosion if evaporation and diffusion should occur during the time between filling the chambers and ignition. Tests of representative materials used in the Gemini and Apollo spacecraft were desired, although, for initial tests, simple materials were preferred because of the need to understand the mechanisms involved. The following criteria were used for selecting fuels:

1. The fuel should be relatively pure without foreign materials that might catalyze or restrict reactions.
2. The fuel must be capable of existing in an oxygen environment at 5 psia for 24 hours without any significant change in properties, or without emitting sufficient flammable gas to result in the formation of an explosive mixture.
3. The fuel should be free of chemically bound oxygen which would allow ignition to proceed without atmospheric support.

4. The combustion products should be mostly gaseous, with solid ash or soot being only a minor product of combustion.
5. The fuel must have a high vapor pressure and be readily ignited.
6. Fuels should possess an interval of 50° to 75° C between melting and boiling points.

Atmospheres

Three atmospheric compositions were used in one-gravity bench tests: air, pure oxygen, and a 50-50 mixture by volume of nitrogen and oxygen. Pressures varied from 2 1/2 to 20 psia. Temperatures prior to ignition ranged from 35° to 70° F. Problems associated with ignition, burning rates, and the effect of pressure changes were investigated. Chamber volume was the same for all bench tests and zero-gravity tests. Pressure was found to rise during the burning tests, but the effect was negligible. Pressure rises of 1 to 3 inches of mercury were common, and varied with the fuel composition, quantity, and structure. As soon as the flame was extinguished, however, chamber pressures returned to within 1 inch of mercury of the starting pressure, or below the starting pressure by as much as 2 inches of mercury after cooling. The significant factors affecting pressure were the expansion of the heated gases during burning, and the subsequent contraction due to condensation of water vapor during cooling of the chamber.

Ignition

A 24-volt dc source was selected for ignition because it was available on the aircraft and was required by the motors of the Milliken cameras. The igniter was a 5 1/2-inch length of 20-gage Nichrome wire. This wire furnished adequate heat to ignite most materials touching it in the three atmospheres selected. The wire was heavy enough to give physical support to fuels, and yet sufficiently light not to be a significant heat sink during burning. The wire heated to the melting point and broke in approximately 2 seconds, thus discontinuing heat input. A maximum current of 40 to 48 amperes was required. A maximum temperature of 2550° F was obtained as determined by handbook data of the melting point of Nichrome.

Photographic Coverage

The pertinent information was obtained by high-speed photography. Sixteen-millimeter color film (ER-B) to show nature of combustion, and infra-red sensitive film to show contrasting thermal flame profiles were selected. Supplemental lighting was not necessary since satisfactory performance was obtained from the ignition flame. A focal length of 12 inches from the fuel to the film plane was selected, with a field of view of approximately 5 by 7 inches.

ZERO-GRAVITY TESTS

Fifteen flammability chambers were prepared in which a variety of fuels and atmospheres were used. The filling operation consisted of loading the chambers with an igniter wire and fuel, followed by bolting the cover in place. A mechanical vacuum pump was used to remove the air from the chamber to less than 1 mm Hg pressure. The pressure change, if any, was noted after a period of 12 hours or more in order to identify leaks. If the chambers were found to be airtight, they were pressurized with oxygen (grade MIL-0-27210A). Cameras were mounted on the chambers. The chambers were then transported to the aircraft. The flights in which fuel was burned are listed in table I with fuel composition, fuel weight, gas composition and pressure, zero-gravity time, and photographic coverage. After the flight, the unopened containers were transported to the laboratory where pressures were measured and gas samples withdrawn for analyses. Chambers were then opened and, after cleaning with a dry cloth, were used again. Figures 2 to 4 show the flammability chambers in the C-131 airplane. Figure 2 shows the camera electrical plug being connected; figures 3 and 4 show a weightless chamber during two separate flight parabolas, illustrating a "floor launch" and a "hand-release launch" respectively.

Figures 5(a) to 5(e) show ignition of styrene samples (identified as chamber 16 on table I). The five pictures taken at 1/200-second intervals, show how readily ignition occurred in zero gravity. Other fuels, photographed in the same manner, show similar, rapid ignition. Figures 5(f) to 5(v) show sequences, at 1/5-second intervals, of styrene immediately after ignition. Figures 6(a) to 6(d) show ignition of white foam rubber (chamber 15, table I) under conditions similar to those used with styrene, and figures 6(e) to 6(l) show 1/5-second sequences of the ignition. In both burnings the flame was diminished and darkened, although no actual self-extinguishment occurred. In the burning of styrene the igniter wire produced heat for 1.42 seconds (fig. 5(l)). Figures 5(m) to 5(v) show the wire was cooling by conduction and

radiation. Despite the continual heat input for more than 1.42 seconds, the flame is maximum in size and brilliance at time $t = 1.02$ seconds (fig. 5(j)). The photographs of foam rubber combustion show the wire breaking between 0.62 and 0.82 second (figs. 6(g) and 6(d)). In this case, the flame maximum size appeared to coincide with the time the electrical heat input ceases. Both the styrene and foam rubber continued to burn at a decreasing rate for the duration of the weightlessness. Figures 7(a) to 7(h) are photographs taken at intervals of 1/200 second showing ignition of paraffin in a weightless environment. Figures 7(i) to 7(k) show the combustion of paraffin continuing at 1/5-second intervals. Figures 7(l) to 7(r) show the sequence continuing without visible flame and with the igniter wire cooling. The film, following figure 7(r), shows the wire eventually becoming invisible; the flame reappeared after an acceleration-created convection was induced. The appearance of the flame was very gradual, starting with a pinpoint of light. The first reappearance was for 0.1 second, after the fire appeared to be extinguished for 4.25 seconds. This reappearance was a gradual buildup from a pinpoint of light to an extremely small flame, followed by a second period of non-illumination. Figure 7(s), at time $t = 6.30$ seconds, shows the second reappearance, and shows a phase of a steadily increasing flame which first appeared as a pinpoint 0.09 second earlier. The appearance of the flame also indicated that weightlessness had ended, coinciding with observed float time of 6 seconds as recorded by an observer. All times are based on the assumption of a constant camera speed of 200 frames per second. The possible error induced by variation of camera speed as a result of using more than one camera is estimated to be less than 5 percent. On several occasions, the imposed acceleration was due to a slight brush with the side of the aircraft, which produced gravitational fields of less than one gravity. At other times, the impact of the chamber with the aircraft was considerably greater than one gravity. Figures 8(a) to 8(e) show the result of an impact experienced after 5 seconds of burning (chamber 19, table I).

A test using paraffin (chamber 56, table I) is shown in figures 9(a) to 9(j). The atmosphere for this test was a 50-percent by volume mixture of oxygen and nitrogen at 10 psia. The ignition is shown in figures 9(a) to 9(e), with the sequence taken at 1/200-second intervals. The burning of the paraffin immediately after ignition is shown in figures 9(f) to 9(j) with the series taken at 1/5-second intervals. Again, the flame is seen to diminish and darken during the first second of burning.

Infrared photographs of paraffin burning in zero gravity are shown in figures 10(a) to 10(d) and 11(a) to 11(e). Figures 10(a) to 10(d) give a sequence at 1/100-second intervals of the paraffin ignition identified as chamber 22, table I. Figures 11(a) to 11(e) apply to paraffin ignition identified

as chamber 10. The photograph of figure 11(c) was taken immediately following the flame disappearance, and figure 11(e) shows a first reappearance of flame.

RESULTS

A total of 35 flammability experiments were conducted. Thirty-two of these experiments resulted in ignition, of which 26 were photographed. Color photography at 200 frames per second, infrared photography at 100 frames per second, and free-float time for some of the tests, were the only data recorded during flight.

Regression

In many cases of fuels burning in zero gravity, the flame darkens and diminishes. The styrene flame was maximum at $t = 1.02$ seconds (fig. 5(j)); whereas, the heat input continued until $t = 1.42$ seconds (fig. 5(l)). Regression of the flame continued for the duration of weightlessness. The foam rubber flame, on the other hand, reached a maximum at $t = 0.82$ second, immediately following the termination of heat input (fig. 6(h)). Again, regression continued for the duration of weightlessness. Paraffin exhibited the largest flame corona at $t = 0.44$ second (fig. 7(j)), just preceding the breaking of the igniter wire. The flame regressed rapidly to total extinguishment. The first reappearance of flame was for only 1/10 second, including both the build-up and regression to extinguishment. Figure 9(h) shows the maximum size for the other paraffin flame shown pictorially in this report. Other fuels not included in the figures showed a similar regression starting in the first 1.5 seconds and continuing until either weightlessness ended or until self-extinguishment occurred.

Self-Extinguishment

Self-extinguishment appeared to take place in several burnings during zero gravity. When the gravitational force field was re-instituted by the flammability chamber striking the wall or floor of the cabin, the convection in every case caused the flame to re-establish itself. Time intervals of approximately 10 seconds were insufficient to permit a chain of events including ignition, propagation of flame around the fuel, regression of flame because of the gradual reduction in oxygen concentration, and sufficient cooling so that fresh oxygen would not cause the fire to rekindle.

Flame Corona

The flame corona varies according to the fuel and atmosphere. The shape of the flame corona is spherical or dome-shaped according to the outflow of gas from the fuel and the shape of the solid fuel (fig. 6(i)). The flowing particles viewed clearly in the motion pictures give a clue to the interface between the atmosphere and the corona. In figure 6(i) the migration of particles outward is completely random, whereas in figure 5(k) there is a noticeable deflection of the particles to a central point where they depart through a region less sharply defined. Figure 7(j), on the other hand, shows a corona that seems to have a completely undefined interface.

DISCUSSION OF COMBUSTION UNDER ZERO-GRAVITY CONDITIONS

A material burns because of the chemical union of an oxidizable component with oxygen. Under normal conditions, combustion is accompanied by flame. A flame is produced when the chemical reactions of the fuel with oxygen release thermal energy to the surroundings through gradients in proximity to the fuel, in such a manner as to cause coupling of the reaction rates to the physical forces associated with material and energy transport. The union of a fuel with oxygen can be represented by a set of related chemical reactions, the sum of which shows the starting reactants and the final products. A release of energy to the surroundings results. Thus, for methane burning in excess oxygen, the sum of all chemical reactions is $\text{CH}_4 + 2\text{O}_2 \rightarrow \text{CO}_2 + 2\text{H}_2\text{O}$ (plus 210.8 kg cal per gram molecular weight of gas burned). The chemical reactions depend on the fuel being burned. The set of chemical reactions representing each step in combustion to yield the final net reaction is called the chemical reaction mechanism.

The chemical reaction mechanism becomes coupled with the transport forces (ref. 4), which for ordinary combustion on earth are (1) diffusion of gases through each other, (2) gravitational convection, (3) resistance or drag due to gas viscosities, (4) thermal conduction, and (5) radiation. The most important of the material and energy transport forces are diffusion, convection, and conduction. On earth, where a gravitational field always exists, convection is ever present. Convection causes the chemical reaction mechanism to take place through a very narrow zone in a flame, one that is only a few tenths of a millimeter in thickness, and having a maximum thermal gradient of $100\,000^\circ\text{C}$ per centimeter (ref. 5), with gas acceleration forces of 1000 times earth gravity, and at gas flow rates across the flame front of approximately 1 meter per second. As a result of the physical forces coupled to the reaction mechanism, a given fuel in oxygen will proceed very rapidly through the reaction chain to the final products of combustion. If there is an

excess of oxygen present, only the end products of the mechanism will result. Convection, therefore, is the dominating driving force because it dictates the narrow size of the reaction zone (ref. 6), with its associated high temperatures which accelerate the chemical reaction rates. This is illustrated in figure 12.

It might be expected that in the absence of convection in a zero-gravity environment, the physical forces are coupled somewhat differently to the chemical reaction mechanism. The flame in zero gravity assumes a spherical or domed shape, tending to surround the fuel mass. The diffusion process becomes the predominant rate-controlling physical force. Thermal gradients are considerably decreased as compared to those established at unit gravity, the reaction zone is thickened, and the gas flow rate in the flame front becomes negligible (ref. 7). The chemical reaction zone therefore has a chance to accumulate concentrations of intermediate reaction products, many of which are free radical species (uncharged fuel fragments possessing unpaired electrons). The relatively large reaction zone, or fireball, contains these accumulated concentrations. It is therefore possible to obtain combustion products in the environs of a zero-gravity flame that are different from the normal end products of combustion. As the reaction zone in zero-gravity burning becomes thicker, the initial oxygen in the reaction zone is expended and the temperature drops, as illustrated in figure 13. When the temperature drops far enough, the reaction rates in the chain mechanism are slowed, regardless of the increased concentrations of reactants in the reaction zone. When the chemical reaction rates become too low to sustain requirements for flame strength, the flame goes out. The reactants will then diffuse completely through the reaction zone which accounts for intermediate reactant species observed in an oxygen-rich atmosphere after a fire.

The foregoing theoretical considerations are validated by experiment. The gross products of combustion were analyzed using both gas chromatograph and mass spectrometer techniques. Oxidation products resulting from zero-gravity combustion of the fuels were determined by chemical analysis. This information was combined with that obtained from the photographs to give an insight into the mechanism of zero-gravity combustion. Under convection conditions in an oxygen-rich atmosphere, the gross products of combustion of hydrocarbons should be CO_2 and H_2O . The majority of the analyses carried out on products resulting from zero-gravity burning showed CO_2 and H_2O (table II). Three of the chemical analyses, however, showed an appreciable amount of CO. The presence of CO in the presence of nitrogen is a difficult species to determine on the mass spectrometer. Eighteen analyses made on a mass spectrometer showed only CO_2 , H_2O , O_2 , and N_2 as the gross products of combustion. Analyses of the same reaction products on a mass

spectrometer by a second laboratory indicated CO_2 , CO , O_2 , N_2 , H_2O , and A (table III). Table IV gives the results of the gas chromatographic analyses in which CO_2 and O_2 only were determined and the balance reported as N_2 , although H_2O , A, and CO could have been present and not detected on the chromatograph. Unfortunately the gases collected for analysis included a mixture obtained from zero-gravity combustion as well as the burning that took place while the aircraft returned to a cruise condition with an imposed force field going as high as 2g.

The analytical procedure was as follows:

The chamber wall temperatures were measured with a contact thermometer accurate to $\pm 1^\circ \text{F}$. Chamber pressures after the zero-gravity tests were measured with an open end mercury manometer connected with rubber and polyethylene tubing through a two-way brass valve to the chamber and to a 100-cc sample bottle and mechanical vacuum pump or to an oil diffusion-mechanical pump combination. The volume of the system from the chamber to the manometer was calculated as less than 0.2 percent of the chamber volume. A residual pressure in the vacuum line of 50 torr results in less than 0.1 percent error in chamber pressure. The accuracy of the chamber pressure listed in table V is limited by the accuracy of the manometer (± 3 torr) and is estimated to be about 1 percent error. Samples were obtained by evacuating 100-cc gas bottles with a mechanical pump and purging for about 5 seconds with gas from the chamber. Samples marked "gas bottle" in table V were stored for later analyses. Those marked "direct" were obtained in the same manner, except the diffusion and mechanical pumps of the mass spectrometer were used for evacuation, and the samples were analyzed immediately. Sample pressures were insignificantly less than reaction chamber pressures because the sample volume was small compared to the chamber volume. Mass spectra of the samples were obtained with a modified CEC model 21-620 mass spectrometer. The range from 2 to 240 atomic mass units was scanned. The spectra indicated the presence of O_2 , CO_2 , H_2O , N_2 , and in some cases, an unidentified species of mass 40, probably argon. For quantitative analysis, the instrument was calibrated with two-component systems of O_2/CO_2 , O_2/N_2 , and $\text{O}_2/\text{H}_2\text{O}$ of known compositions. The latter mixture was obtained by saturation of O_2 at atmospheric pressure and a known temperature. In view of the results obtained on the second mass spectral analysis of some of the samples, the system O_2/CO of known composition should have been used for calibrating the mass spectrometer which was used to obtain the data shown in table II.

Since the pressure in the reaction chambers varied little from the initial 5 psia after combustion, the presence of nitrogen in the products could not be explained by leakage after the chambers were filled; techniques used were designed to minimize contamination into the mass spectrometer when the gas samples were transferred to the instrument. Nitrogen contents in some of the analyses appear excessive, and are probably due to air leakage during initial filling of the chambers with oxygen. The $\text{CO}_2/\text{H}_2\text{O}$ concentrations appear unreasonable for combustion of paraffin in excess oxygen, and the water concentrations are not as high as might be expected. The absence of fluorine compounds in the case of teflon burning could be ascribed to subsequent reactions of fluorine compounds with the materials in the chamber. Appreciable concentrations of CO could have been present, but these concentrations may have been concealed in the data shown in table II. Some of the samples from zero-gravity and from unit-gravity combustion were analyzed on an F and M 520 gas chromatograph using a 6-foot column of 1/4 inch o.d. One column was packed with silica gel and the other with molecular sieves 5A. The column temperatures were maintained at 50° C and the filament current maintained at 150 milliamperes. The carrier gas was helium at 60 ml per minute flow, and the sample size was 5 ml.

The gas chromatograph showed the presence of O_2 and CO_2 . The balance of the constituents were classed as N_2 , although CO and H_2O and other gaseous species probably were present in the remaining gas.

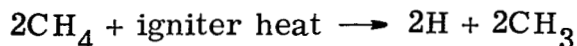
It is noted that two specimens of paraffin which were burned in a 5-psia oxygen atmosphere at zero gravity gave a yield of carbon monoxide as follows:

<u>Specimen</u>	<u>Fuel weight, grams</u>	<u>Gravity condition</u>	<u>Mol percent of CO</u>
7	0.1521	zero gravity	3.58
14	0.6838	zero gravity	2.37

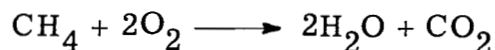
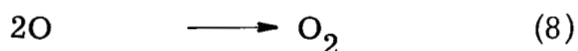
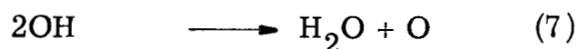
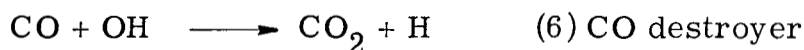
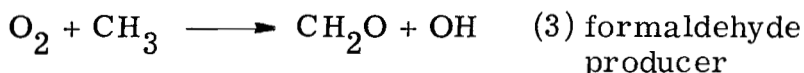
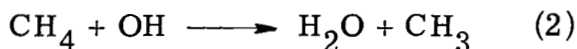
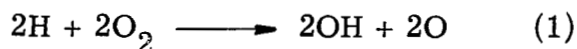
Twelve other paraffin samples ignited in zero gravity showed no detectable CO at varying oxygen concentrations. The presence of CO in an excess of oxygen in the two-gas mixtures previously discussed is explained on the basis of the chemical reaction mechanism for hydrocarbon combustion, as follows:

Paraffin, like polyethylene, is a straight-chain hydrocarbon saturated with respect to hydrogen. The simplest member of a straight-chain hydrocarbon series is methane CH_4 . A combustion mechanism for methane may be written thus:

The energy of the igniter ruptures the hydrocarbon chain and breaks off a hydrogen atom.



The chemical combustion mechanism is now set to proceed as follows:



An explanation for CO existing after zero-gravity burning of paraffin follows from step (5) in the mechanism. Some of the HCO free radicals (step 5) must diffuse through the reaction zone to the outside surroundings and liberate the CO under conditions where the OH free radical is not present to oxidize it to CO₂, as observed in step (6). Similarly, the oxidation of formaldehyde, CH₂O, in step (4) in zero gravity is dependent on diffusion for union with the O atom produced near the fuel by step (1). If some of the formaldehyde formed in step (3) should diffuse away from the reaction zone during zero-gravity conditions, the molecules will remain as formaldehyde. In addition to CO and CH₂O, large quantities of the lower chain fragments and free radicals from the original fuel decomposition during zero-gravity combustion would be expected as final combustion products. In zero gravity it is probable

that part of the lower chain fragments will diffuse to cooler zones where oxidation rates subsequently become negligible. The observed phenomena shown on the films and the results obtained by chemical analysis can be explained on the basis of the foregoing mechanism.

Several distinctive color flashes observed on the film when paraffin re-ignites after a period of time in zero gravity are typical of free radical combinations. The re-ignition of the fuels in oxygen as a gravitational field imposed after zero-gravity burning, particularly the explosive character of the flame noted from paraffin fuels, points to the presence of free radicals and fuel fragments waiting to be oxidized and to flame when oxygen becomes accessible. The intermittent flashes of light observed from paraffin burning in zero gravity after the flame has gone out may indicate the diffusion of the free radical species through the reaction zone, which has become too cool to sustain the flame strength. A possibility also exists that gases trapped in the asbestos fiber caused the sputtering noted.

Teflon is a fluorocarbon polymer and will not burn noticeably in air. In a 5 psia oxygen atmosphere, teflon will ignite and burn in zero gravity and in unit gravity. Analysis of the reaction products resulting from teflon burning in 5 psia oxygen at zero gravity showed only 1 mol percent of CO_2 , whereas other fuels burned showed from 3 to 18 times more CO_2 . Relatively few of the carbon-fluorine bonds were ruptured by the ignition or by the burning process; therefore, the products of combustion must be compounds of carbon, oxygen, and fluorine. Compounds of fluorine were not found in the mass spectrographic analyses of the combustion products.

RECOMMENDATIONS

In order to provide design criteria for fire-extinguishment equipment and techniques, it is recommended that the following areas be investigated:

1. Continue zero-gravity investigations using thermocouples to give temperature profiles.
2. Continue zero-gravity investigations with longer test times to learn if a flame, once apparently extinguished, will remain extinguished when oxygen diffuses naturally into the flame zone.
3. Analyze gases taken from various points in the flame to determine chemical species and to gain an insight of the reaction kinetics.

4. Study the effects of a sudden decrease in total pressure from 10 to 3 inches of mercury (pressure at 50 000 ft) which is the lowest pressure in which man can survive without a pressure suit.
5. Study the effects of impinging dry solids such as sodium bicarbonate and potassium bicarbonate into the zero-gravity flame zone.
6. Observe the effects of various high gravity forces by use of a centrifuge.
7. Compare the effects of various induced convective forces on the cabin atmosphere of manned spacecraft.
8. Measure properties in zero gravity such as ignition temperatures, surface propagation rates, and combustion rates for various fuels and atmospheres.
9. Investigate the flame interface to determine if a phenomenon comparable to surface tension exists.
10. Evaluate the effects of ash forming during flammability in zero gravity of solid fuels such as magnesium, titanium, and other metals.
11. Evaluate the effects of a heat sink to prevent a flame, once extinguished, from being rekindled in zero gravity should oxygen circulation be established.

CONCLUSIONS

The following conclusions can be drawn from this study:

1. Steady-state burning common in one-gravity conditions does not always take place in zero gravity.
2. Ignition energy at zero gravity is quantitatively of the same order of magnitude as in one gravity.
3. The flame, which possesses a spherical or dome-shaped corona, becomes progressively darker and smaller as solids burn in zero gravity.
4. Fire will propagate along the surface of a solid under zero-gravity conditions.

5. Adding a force field promptly renews convection and gives a marked increase in burning rates.

6. Inert gases suppress combustion.

7. Flame coronas under zero-gravity conditions have different characteristics.

8. Photographic evidence obtained, as well as finding CO as a product from oxygen-rich zero-gravity combustion, support a mechanism for zero-gravity combustion for which the rates of chemical reactions representing the changes taking place are coupled only to the diffusion transport force. The flame in zero gravity, therefore, is largely a diffusion limited flame.

Manned Spacecraft Center

National Aeronautics and Space Administration

Houston, Texas, March 29, 1966

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4. Spalding, D. B.: Experiments on the Burning and Extinction of Liquid Fuel Spheres. FUEL, vol. 32, 1953, pp. 169-185.
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6. Spalding, D. B.: The Combustion of Liquid Fuels. Fourth International Symposium on Combustion, 1953, pp. 847 ff.
7. Wise, Henry; Lorell, Jack; and Wood, Bernard J.: The Effects of Chemical and Physical Parameters on the Burning Rate of a Liquid Droplet. Combustion Institute Fifth Symposium (International) on Combustion, University of Pittsburgh, April 15, 1964, pp. 132 ff.

TABLE I. - ZERO-GRAVITY BURNING EXPERIMENTS

Date	Chamber	Fuel	Weight, grams	Atmosphere		Burn	Time in zero g, sec	Photography
				Composition	Pressure, psia			
1-7-64	12	Paraffin	0.1476	O ₂	5	Yes	Not recorded	Color
1-7-64	7	Paraffin	.1521	O ₂	5	Yes	Not recorded	Color
1-7-64	3	Neoprene	.5737	O ₂	5	Yes	Not recorded	Color
1-7-64	14	Paraffin	.6838	O ₂	5	Yes	Not recorded	Color
1-7-64	2	Nylon	.2712	O ₂	5	Yes	Not recorded	Color
1-7-64	8	Paraffin	.6167	O ₂	5	Yes	Not recorded	Color
1-7-64	6	Teflon	.2098	O ₂	5	Yes	Not recorded	Color
1-7-64	1	Polyester, G. F.	1.3241	O ₂	5	Yes	Not recorded	Color
1-7-64	5	Black foam rubber	.6725	O ₂	5	Yes	Not recorded	Color
1-7-64	9	Paraffin	.8590	O ₂	5	Yes	Not recorded	Color
1-14-64	16	Styrene	1.0003	O ₂	5	Yes	Not recorded	Color
1-14-64	17	Paraffin	.1264	21 percent O ₂	14.7	No	Not recorded	Color
1-14-64	4	Epon 828	.4848 *	O ₂	5	Yes	Not recorded	Color
1-14-64	20	ERB ph. film	2 in. long	O ₂	5	Yes	Less than 1	Color
1-14-64	21	Silic. O-Ring	.1837	O ₂	5	Yes	3	Color
1-14-64	22	Paraffin	.1524	O ₂	5	Yes	Not recorded	I. R.
1-14-64	24	Teflon	.2534	O ₂	5	Yes	3	Color
1-14-64	10	Paraffin	.5680	O ₂	5	Yes	3	I. R.

TABLE I. - ZERO-GRAVITY BURNING EXPERIMENTS - Continued

Date	Chamber	Fuel	Weight, grams	Atmosphere		Burn	Time in zero g, sec	Photography
				Composition	Pressure, psia			
1-14-64	41	Match, Safety	1 5/8 in.	O ₂	5	Yes	5	Color
1-14-64	27	Phenol, F. G.	1.3548	O ₂	5	No	More than 5	Color
1-14-64	28	Paraffin	0.1244	O ₂	14.7	Yes	5	Color
1-14-64	29	Tygon	.7269	O ₂	5	Yes	6	Color
1-14-64	15	White foam rubber	.2706	O ₂	5	Yes	6	Color
1-15-64	31	Nylon cord	.1804	O ₂	5	Yes	5	Color
1-15-64	32	Paraffin	.8509	O ₂	5	Yes	11	Color
1-15-64	19	Paraffin	.1084	O ₂	14.7	Yes	5 to 8	Color
1-15-64	35	Paraffin	.7213	21 percent O ₂	14.7	Yes	10	Color
1-15-64	36	Paraffin	.1551	50 percent O ₂	10	Yes	3 to 8	Color
1-15-64	37	Tygon	.5740	O ₂	14.7	Yes	10 to 11	Color
1-15-64	23	Polyester, G. F.	1.3971	O ₂	5	Yes	10 to 11	Color
1-15-64	56	Paraffin	.1636	50 percent O ₂	10	Yes	7 to 12	Color
1-15-64	42	Phenol, F. G.	1.3548	O ₂	5	Yes	4 to 5	Color
1-15-64	43	Phenol, F. G.	1.2866	O ₂	5	Yes	9 to 13	Color

TABLE I. - ZERO-GRAVITY BURNING EXPERIMENTS - Concluded

Date	Chamber	Fuel	Weight, grams	Atmosphere		Burn	Time in zero g, sec	Photography
				Composition	Pressure, psia			
1-15-64	44	Silic. O-Ring	0.0854	O ₂	14.7	Yes	8 to 12	Color
1-15-64	30	Paper, bleached	1 by 2 in.	O ₂	5	Yes	9 to 12	Color

Totals

353226

Notes:

1. Pressures are nominal. Not all gages calibrated. Variation ± 10 percent.
2. For percentage O₂ given, consider balance dry nitrogen.
3. For 21 percent O₂ given atmosphere was air of 60 ± 10 relative humidity.

TABLE II. - ANALYSES OF PRODUCTS OF COMBUSTION FROM FLAME REACTIONS
USING MASS SPECTROMETER TECHNIQUES

Sample	Material	Weight of sample, grams	Flame conditions at 5 psia O ₂ , g	Mol fractions determined			
				O ₂	CO ₂	H ₂ O	N ₂
1	Polyester	1.3241	Zero-g	0.91	0.05	0.02	0.02
2	Nylon	0.2712	Zero-g	.92	.04	.02	.02
3	Neoprene	.5737	Zero-g	.83	.10	.02	.05
5	Foam rubber	.6725	Zero-g	.82	.11	.02	.05
6	Teflon	.2098	Zero-g	.88	.01	.02	.09
7	Paraffin	.1521	Zero-g	.87	.04	.03	.06
8	Paraffin	.6167	Zero-g	.69	.10	.03	.18
9	Paraffin	.8590	Zero-g	.70	.16	.02	.12
10	Paraffin	.5680	Zero-g	.81	.13	.03	.03
11	Paraffin	.1357	One-g	.91	.03	.03	.04
12	Paraffin	.1476	Zero-g	.41	.01	.03	.55
13	Paraffin	.1482	One-g	.87	.03	.02	.08
14	Paraffin	.6838	Zero-g	.77	.18	.02	.03
16	Styrene	1.0003	Zero-g	.42	.08	.03	.47
18	Paraffin	.1562	One-g	.88	.04	.02	.06
22	Paraffin	.1524	Zero-g	.78	.03	.05	.15
24	Teflon	.2534	Zero-g	.88	.01	.01	.10
26	Paraffin	.1550	One-g	.89	.04	.02	.05
Lot 110 oxygen gas				.99	--	--	.01
Lot 130 oxygen gas				.98	--	--	.02

TABLE III. - ANALYSES OF PRODUCTS OF COMBUSTION FROM FLAME
REACTIONS USING MASS SPECTROMETER TECHNIQUES

Sample	Material	Weight of sample, grams	Flame conditions at 5 psia O ₂ , g	Mol fractions determined					
				H ₂ O	CO ₂	CO	A	N ₂	O ₂
2	Nylon	0.2712	Zero-g	0.0107	0.0342	----	0.0140	0.0186	0.9351
5	Foam rubber	.6725	Zero-g	.0068	.1031	0.0049	.0019	.0751	.8082
6	Teflon	.2098	Zero-g	.0065	.0015	----	.0100	.7526	.2294
7	Paraffin	.1521	Zero-g	.0064	.0157	.0358	.0068	.4482	.4871
12	Paraffin	.1476	Zero-g	.0044	.0167	----	.0007	.4445	.5337
14	Paraffin	.6838	Zero-g	.0117	.0592	.0237	.0070	.4776	.4208

TABLE IV. - ANALYSES OF PRODUCTS OF COMBUSTION FROM
FLAME REACTIONS USING GAS CHROMATOGRAPH

Sample	Material	Weight of sample, grams	Flame conditions at 5 psia O ₂ , g	Mol fractions determined		
				CO ₂	O ₂	Others (reported as N ₂)
1	Polyester	1.3241	Zero-g	0.033	0.930	0.038
2	Nylon	0.2712	Zero-g	.018	.805	.178
5	Foam rubber	.6725	Zero-g	.044	.682	.276
6	Teflon	.2098	Zero-g	.035	.821	.151
7	Paraffin	.1521	Zero-g	.019	.742	.240
8	Paraffin	.6167	Zero-g	--	--	--
9	Paraffin	.8590	Zero-g	.093	.662	.247
12	Paraffin	.1476	Zero-g	.018	.850	.132
14	Paraffin	.6838	Zero-g	.118	.848	.033
18	Paraffin	.1562	One-g	.026	.900	.072
26	Paraffin	.1550	One-g	.025	.875	.100

TABLE V. - TEMPERATURES, PRESSURES, AND SAMPLING
METHOD OF GAS SAMPLES ANALYZED IN MASS
SPECTROMETER AND REPORTED IN TABLE I

Sample	Material	Pressure in chamber, mm Hg	Temperature of chamber on gas sample withdrawal, °F	Sampling method
1	Polyester	265	76	Direct
2	Nylon	449	74	Direct
3	Neoprene	299	74	Gas bottle
5	Foam rubber	282	74	Direct
6	Teflon	335	74	Direct
7	Paraffin	220	74	Direct
8	Paraffin	306	76	Direct
9	Paraffin	281	74	Gas bottle
10	Paraffin	267	70	Gas bottle
11	Paraffin	280	76	Gas bottle
12	Paraffin	253	73	Gas bottle
13	Paraffin	251	76	Direct
14	Paraffin	261	74	Gas bottle
16	Styrene	253	70	Gas bottle
18	Paraffin	267	76	Direct
22	Paraffin	286	70	Direct
24	Teflon	284	70	Gas bottle
26	Paraffin	276	76	Direct

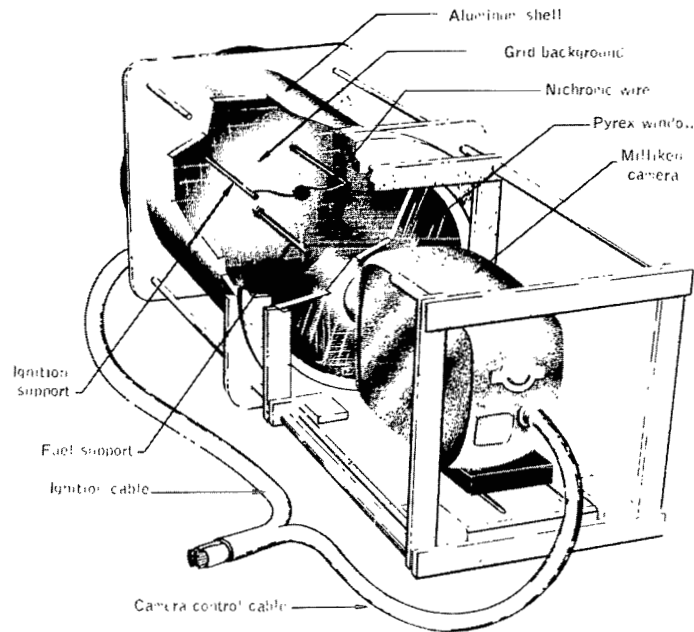


Figure 1. - Zero-g flammability chamber .

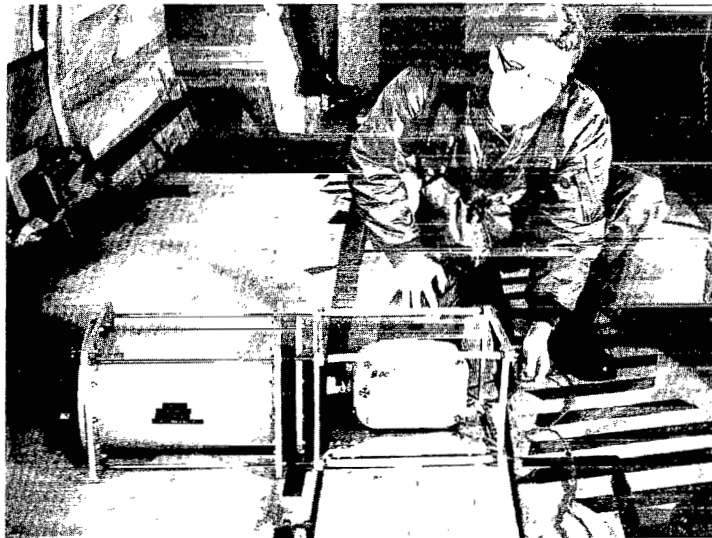


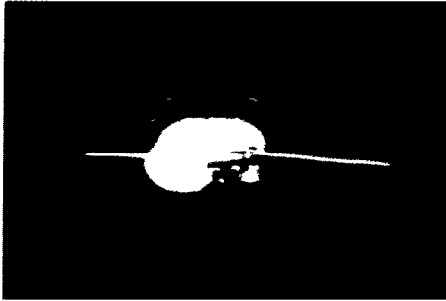
Figure 2. - Flammability chamber in C-131 aircraft showing connection of power cable to camera.



Figure 3. - Flammability chamber weightless after floor launch.

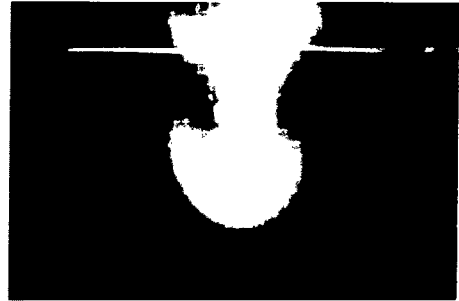


Figure 4. - Flammability chamber weightless in the C-131 aircraft after hand release.



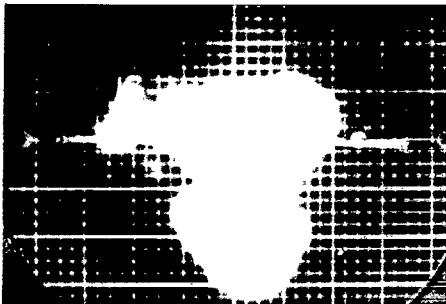
(a) Ignition of styrene under zero g.

Figure 5. - Ignition of styrene
under g.



(b) $t = 0.005$ sec.

Figure 5. - Continued.



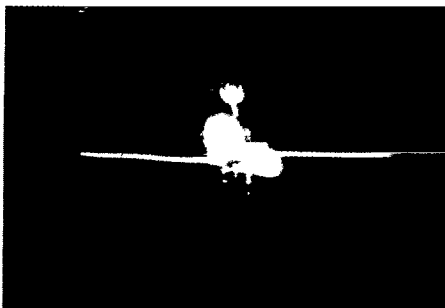
(c) $t = 0.010$ sec.

Figure 5. - Continued.



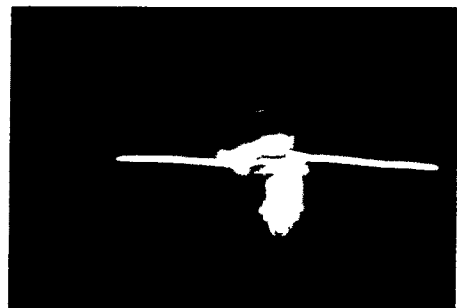
(d) $t = 0.015$ sec

Figure 5. - Continued.



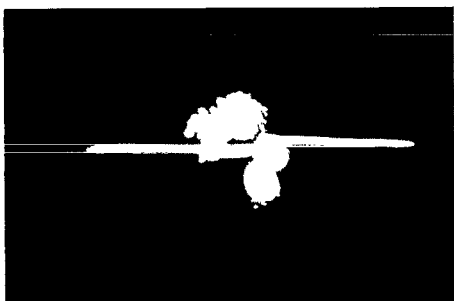
(e) $t = 0.020$ sec.

Figure 5. - Continued.



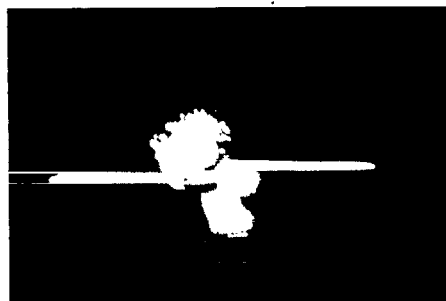
(f) $t = 0.22$ sec, immediately
after ignition.

Figure 5. - Continued.



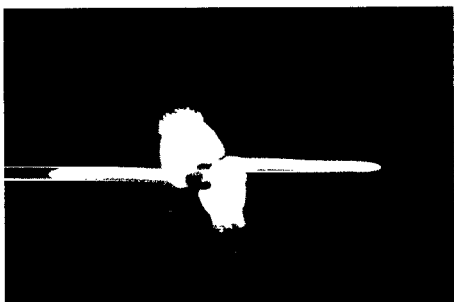
(g) $t = 0.42 \text{ sec.}$

Figure 5. - Continued.



(h) $t = 0.62 \text{ sec.}$

Figure 5. - Continued.



(i) $t = 0.82 \text{ sec.}$

Figure 5. - Continued.



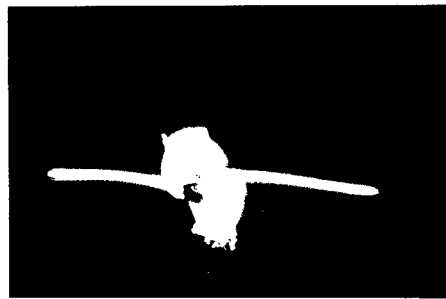
(j) $t = 1.02 \text{ sec.}$

Figure 5. - Continued.



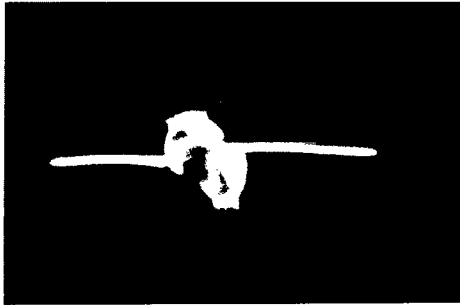
(k) $t = 1.22 \text{ sec.}$

Figure 5. - Continued.



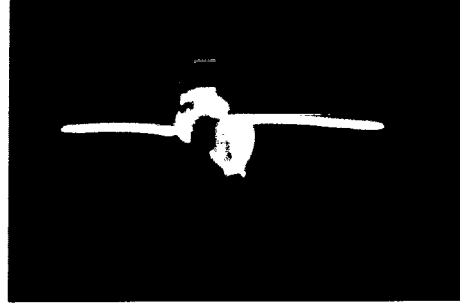
(l) $t = 1.42 \text{ sec.}$

Figure 5. - Continued.



(m) $t = 1.62$ sec.

Figure 5. - Continued.



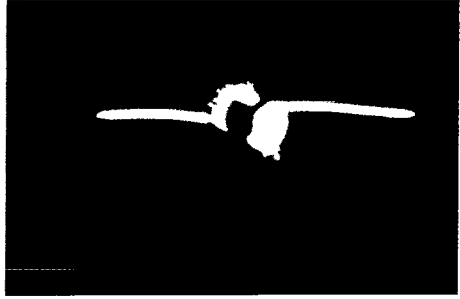
(n) $t = 1.82$ sec.

Figure 5. - Continued.



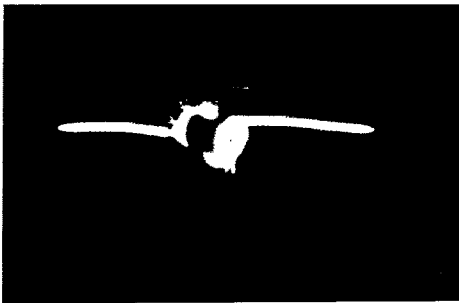
(o) $t = 2.02$ sec.

Figure 5. - Continued.



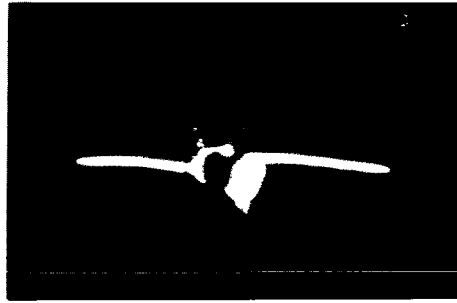
(p) $t = 2.22$ sec.

Figure 5. - Continued.



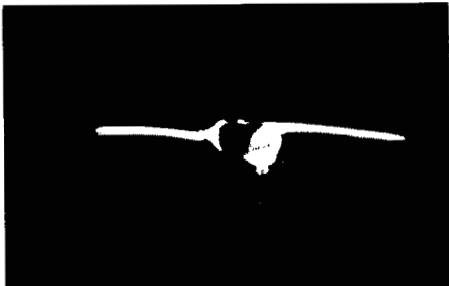
(q) $t = 2.42$ sec.

Figure 5. - Continued.



(r) $t = 2.62$ sec.

Figure 5. - Continued.



(s) $t = 2.82 \text{ sec.}$

Figure 5. - Continued.



(t) $t = 3.02 \text{ sec.}$

Figure 5. - Continued.



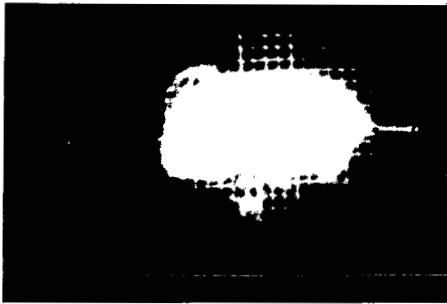
(u) $t = 3.22 \text{ sec.}$

Figure 5. - Continued.



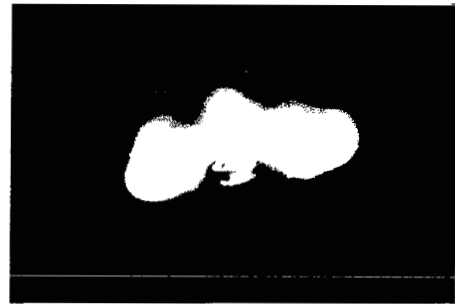
(v) $t = 3.42 \text{ sec.}$

Figure 5. - Concluded.



(a) $t = 0.00$ sec.

Figure 6. - Ignition of foam rubber
under zero g.



(b) $t = 0.005$ sec.

Figure 6. - Continued.



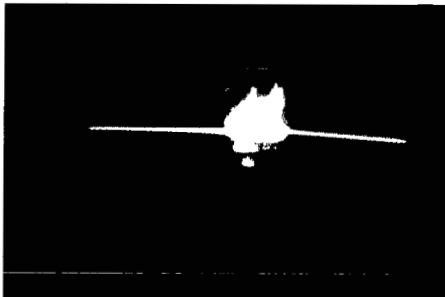
(c) $t = 0.010$ sec.

Figure 6. - Continued.



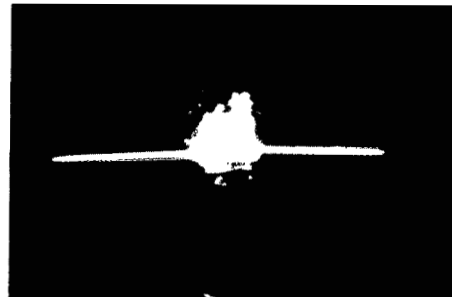
(d) $t = 0.015$ sec.

Figure 6. - Continued.



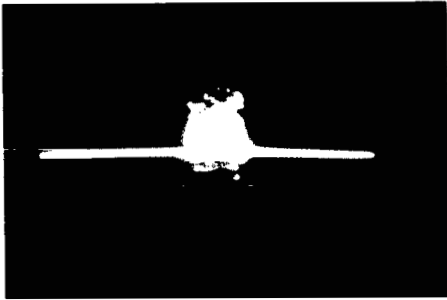
(e) $t = 0.22$ sec, immediately
after ignition.

Figure 6. - Continued.



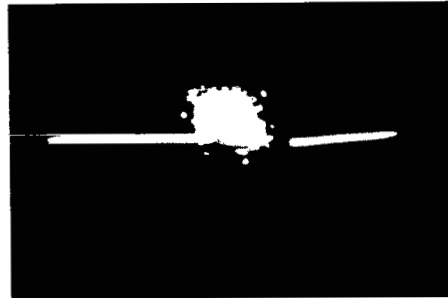
(f) $t = 0.42$ sec.

Figure 6. - Continued.



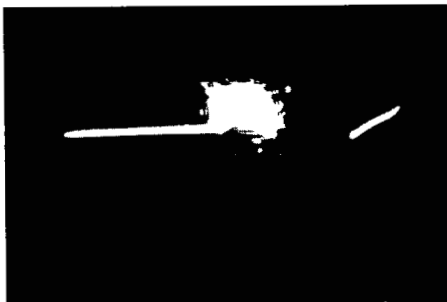
(g) $t = 0.62$ sec.

Figure 6. - Continued.



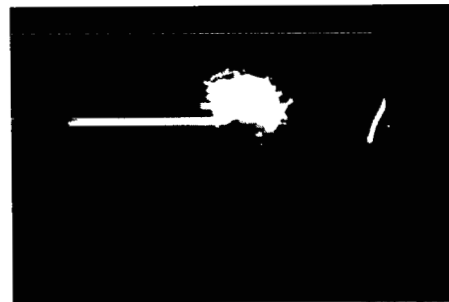
(h) $t = 0.82$ sec.

Figure 6. - Continued.



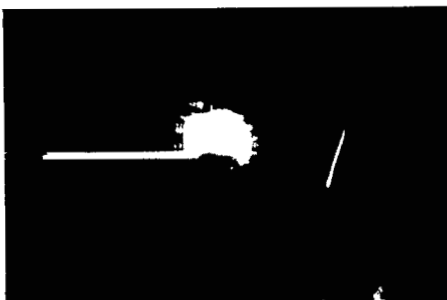
(i) $t = 1.02$ sec.

Figure 6. - Continued.



(j) $t = 1.22$ sec.

Figure 6. - Continued.



(k) $t = 1.42$ sec.

Figure 6. - Continued.



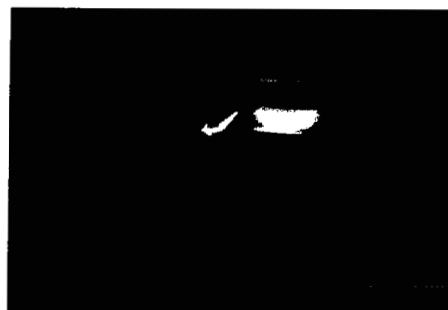
(l) $t = 1.62$ sec.

Figure 6. - Concluded.



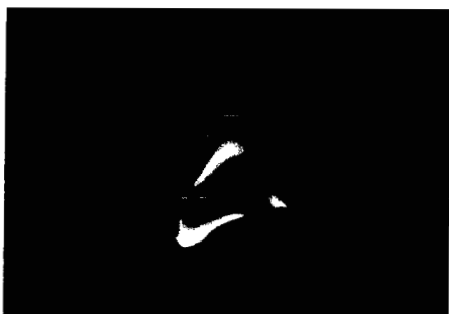
(a) $t = 0.00 \text{ sec.}$

Figure 7. - Ignition of paraffin in
air under zero g.



(b) $t = 0.005 \text{ sec.}$

Figure 7. - Continued.



(c) $t = 0.010 \text{ sec.}$

Figure 7. - Continued.



(d) $t = 0.015 \text{ sec.}$

Figure 7. - Continued.



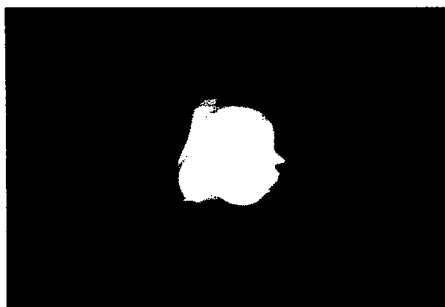
(e) $t = 0.020 \text{ sec.}$

Figure 7. - Continued.



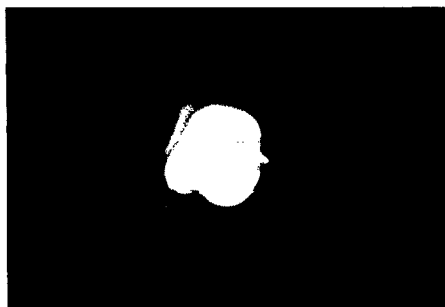
(f) $t = 0.025 \text{ sec.}$

Figure 7. - Continued.



(g) $t = 0.030$ sec.

Figure 7. - Continued.



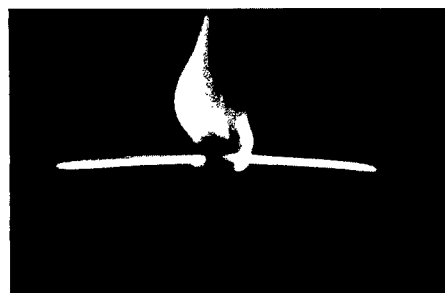
(h) $t = 0.035$ sec.

Figure 7. - Concluded.



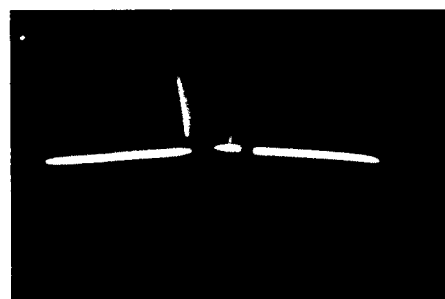
(i) $t = 0.24$ sec, immediately after ignition

Figure 7. - Continued.



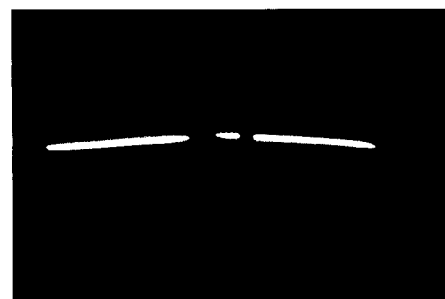
(j) $t = 0.44$ sec.

Figure 7. - Continued.



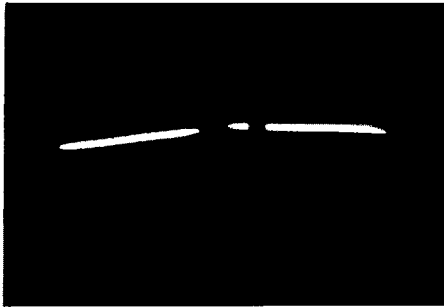
(k) $t = 0.64$ sec

Figure 7. - Continued.



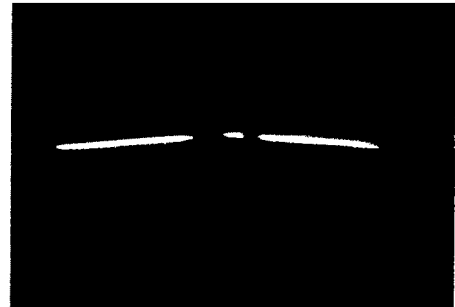
(l) $t = 0.84$ sec, igniter wire cooling
by conduction and radiation

Figure 7. - Continued.



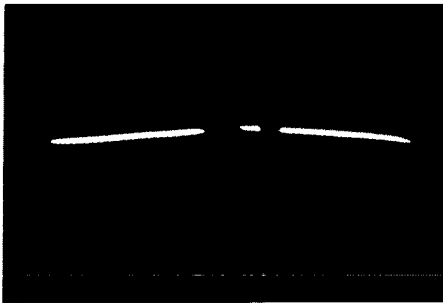
(m) $t = 1.24$ sec.

Figure 7. - Continued.



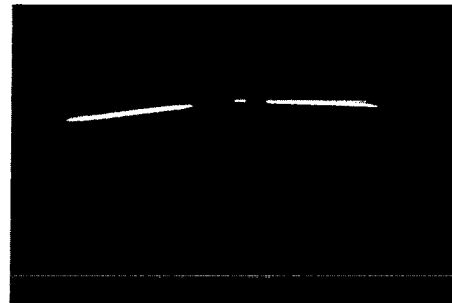
(n) $t = 1.44$ sec.

Figure 7. - Continued.



(o) $t = 1.64$ sec.

Figure 7. - Continued.



(p) $t = 1.84$ sec.

Figure 7. - Continued.



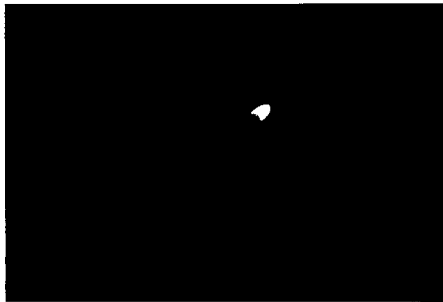
(q) $t = 2.04$ sec.

Figure 7. - Continued.



(r) $t = 2.24$ sec.

Figure 7. - Continued.



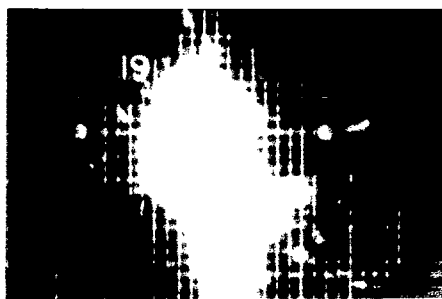
(s) Flame after an initial pinpoint of light 0.09 sec previously. Total interval of darkness was 4.25 sec prior to a 0.1-sec appearance, with 5.7 sec total time from initial darkness until appearance of flame.

Figure 7. - Concluded.



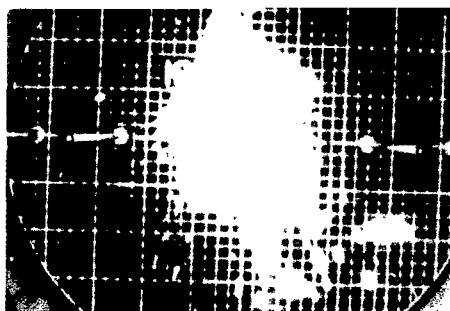
(a) $t = 0.00$ sec.

Figure 8. - Effect of hand impact ending zero g burning of paraffin.



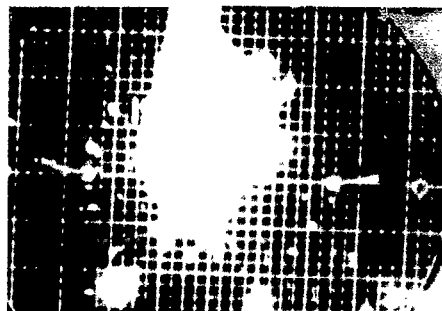
(b) $t = 0.20$ sec.

Figure 8. - Continued.



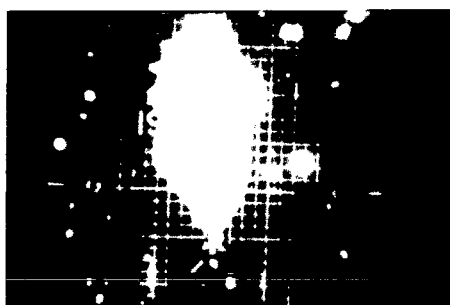
(c) $t = 0.40$ sec.

Figure 8. - Continued.



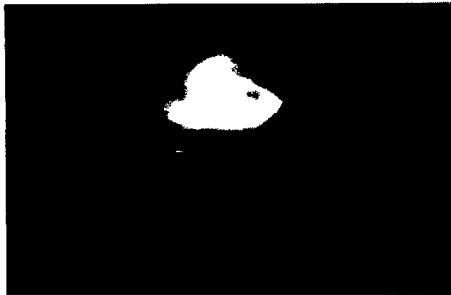
(d) $t = 0.60$ sec.

Figure 8. - Continued.

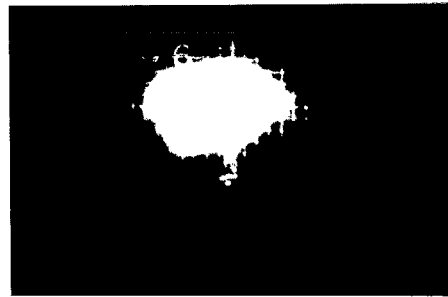


(e) $t = 0.80$ sec.

Figure 8. - Concluded.



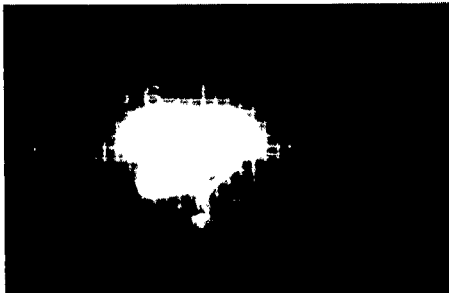
(a) $t = 0.00 \text{ sec.}$



(b) $t = 0.005 \text{ sec.}$

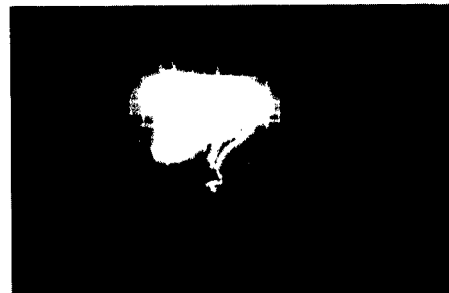
Figure 9. - Ignition of paraffin in a 50-percent oxygen-nitrogen mixture under zero g.

Figure 9. - Continued.



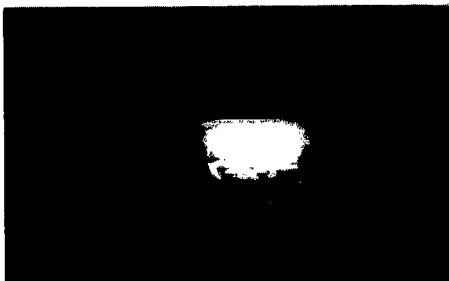
(c) $t = 0.010 \text{ sec.}$

Figure 9. - Continued.



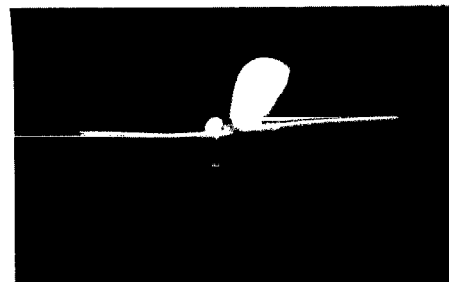
(d) $t = 0.015 \text{ sec.}$

Figure 9. - Continued.



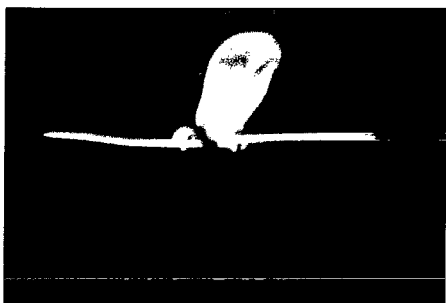
(e) $t = 0.020 \text{ sec.}$

Figure 9. - Continued.



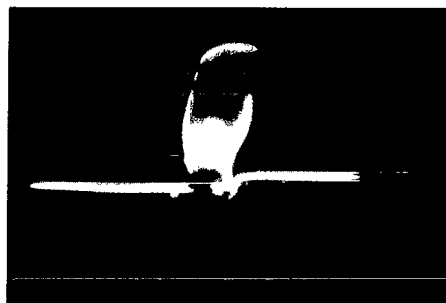
(f) $t = 0.22 \text{ sec, burning under zero g.}$

Figure 9. - Continued.



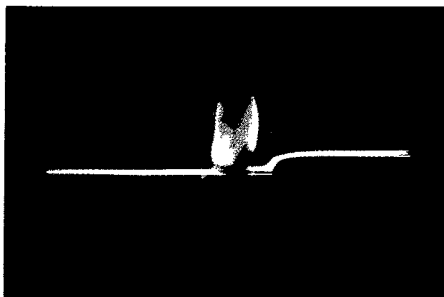
(g) $t = 0.42 \text{ sec.}$

Figure 9. - Continued.



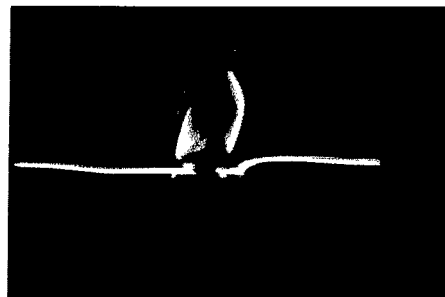
(h) $t = 0.62 \text{ sec.}$

Figure 9. - Continued.



(i) $t = 0.82 \text{ sec.}$

Figure 9. - Continued.



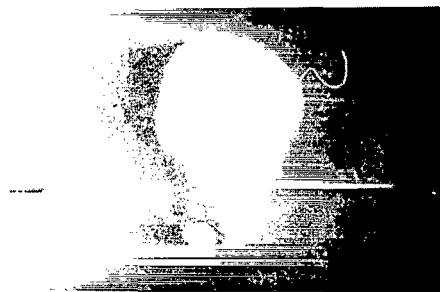
(j) $t = 1.02 \text{ sec.}$

Figure 9. - Concluded.



(a) $t = 0.00 \text{ sec.}$

Figure 10. - Ignition of paraffin under zero g. Infrared film.



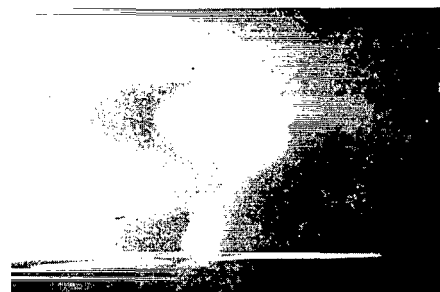
(b) $t = 0.010 \text{ sec.}$

Figure 10. - Continued.



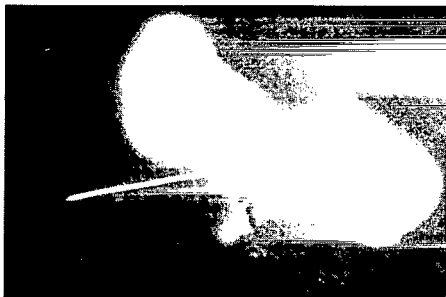
(c) $t = 0.020 \text{ sec.}$

Figure 10. - Continued.



(d) $t = 0.030 \text{ sec.}$

Figure 10. - Concluded.



(a) $t = 0.010$ sec.

Figure 11. - Paraffin burning under zero g.
Infrared film.



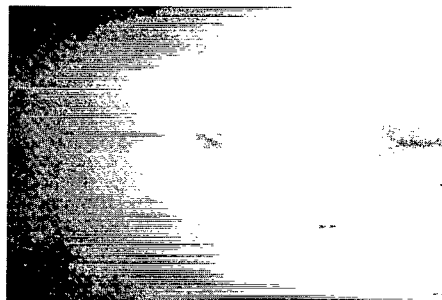
(b) $t = 0.41$ sec.

Figure 11. - Continued.



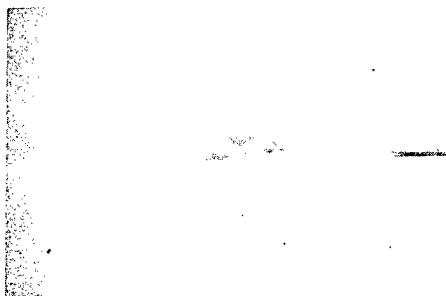
(c) $t = 1.16$ sec immediately following
extinguishment.

Figure 11. - Continued.



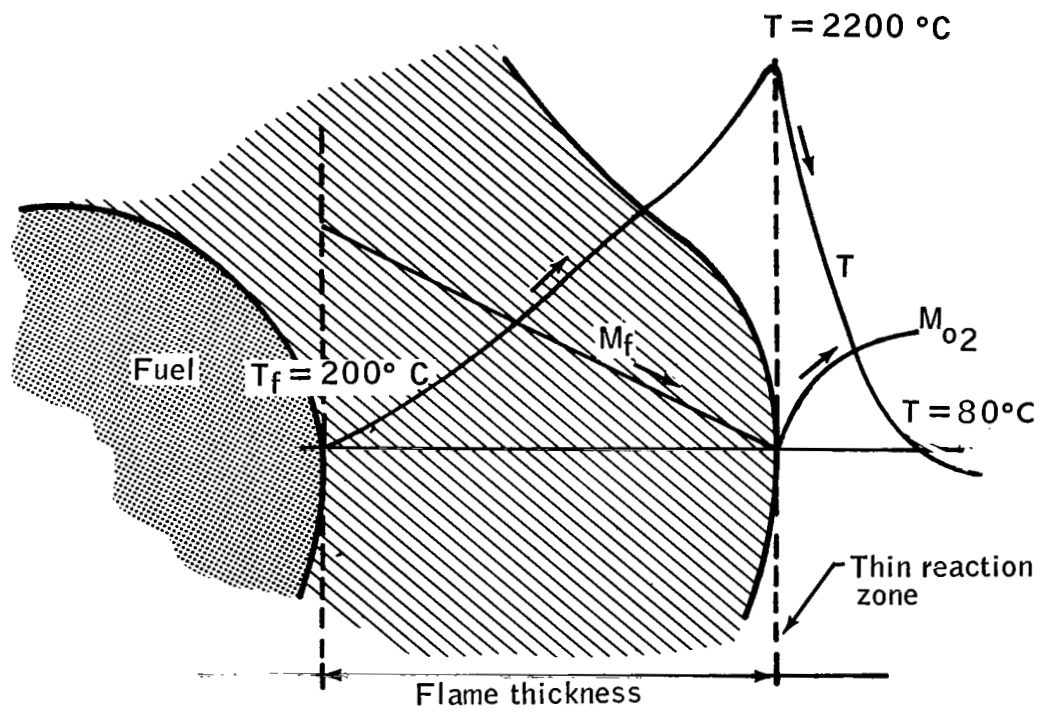
(d) $t = 1.50$ sec.

Figure 11. - Continued.



(e) $t = 7.16$ sec immediately following
flame reappearance.

Figure 11. - Concluded.



M_f = Fuel mass concentration
 M_{O_2} = Oxygen concentration
 T = Temperature, $^\circ \text{C}$

Figure 12. - Combustion under convection conditions.

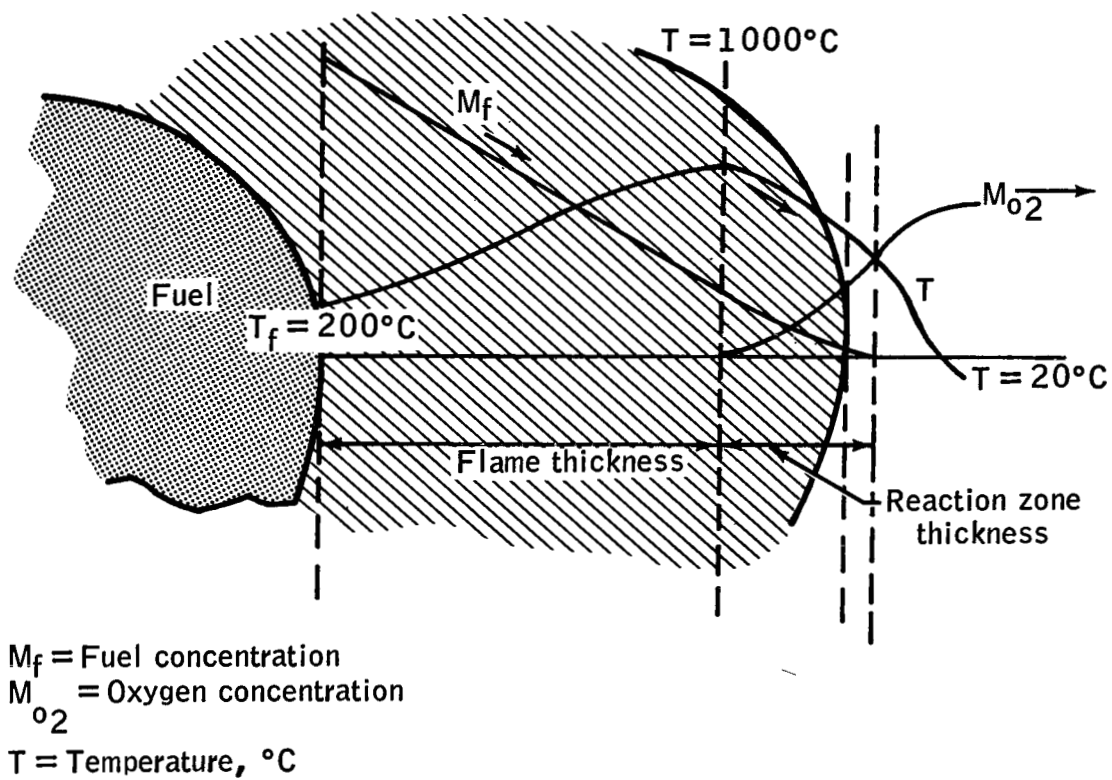


Figure 13. - Postulated combustion conditions under zero gravity.

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—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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